Electron transport in MOVPE grown InGaN/GaN MQW in moderate magnetic field

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1. Introduction The study of magnetic field related electron transport in metalorganic vapour phase epitaxy (MOVPE) grown nitride based 2D heterostructures containing quantum wells (QWs), which are promising for device applications, is of definite interest. There are only a few studies of magnetic field induced transverse electron transport in QWs. However, magnetic field dependent longitudinal (parallel to the quantum well plane) electron transport phenomena, related to transitions between free and localized states of the electrons confined in QWs, could be expected as well.

Emission properties of $In_xGa_{1-x}N$/GaN multiple quantum wells (MQWs) are known to be strongly dominated by the localization of excitons (or carriers) in the potential fluctuations due to the alloy disorder and interface roughness [1]. In MQW structures with x = 0.10−0.15, the localization effects preserv even at room temperature [2]. The latter means that the potential relief of the ground state in the wells is deep enough and a part of the carriers confined in the wells could be frozen−out up to room temperature. Due to the strong localization, magnetic field induced transitions between free and localized states of the electrons confined in QWs, could be expected at high temperatures as well.

In this work we study longitudinal electron transport in InGaN/GaN MQWs at moderate magnetic field up to 1.5 T. Applying an electric field parallel to the sample surface (i.e. to the quantum well plane) and a transverse magnetic field (parallel to the growth direction), we observe a step−wise behaviour of both the Hall coefficient and the magnetoresistivity. Temperature dependencies of the resistivity, Hall mobility, and free electron concentration are studied as well. The observed peculiarities are discussed and a model for their explanation is suggested.

2. Experimental results The investigated MQW structure is grown by MOVPE and consists of five 4−nm−thick quantum wells separated by 10−nm−thick GaN barriers. The molar fraction x of InN is about x = 0.1. The MQW structure is grown on a 2.8−μm−thick Si−doped (n = 1.8x10^{18} cm^{-3}) MOVPE GaN template on sapphire. The longitudinal Hall−effect voltages and resistivity are measured by applying an electric field parallel to the QW plane and a moderate transverse magnetic field up to B = 1.5 T.

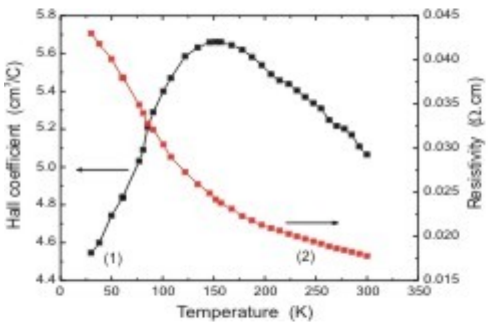

Fig.1 Absolute value of the Hall coefficient (curve 1) and resistivity (curve 2) versus temperature.

The Hall coefficient measured in the temperature range 30−300 K shows a maximum of its absolute value at about 150 K (Fig. 1, curve 1), which is typical for good quality doped GaN samples [3]. The thickness−averaged electron concentration and mobility are dominated by the Si−doped GaN template and vary with the temperature in the ranges (1.2−1.4)x10^{18} cm^{-3} and (96−260) cm^2 /V.s, respectively. While the temperature dependencies of the Hall coefficient and resistivity (Fig. 1, curve 1 and 2, respectively) show a typical character, the magnetic field dependencies exhibit peculiarities, which we study in this work taking into account the parallel conduction paths through the cladding epitaxial layers [4].

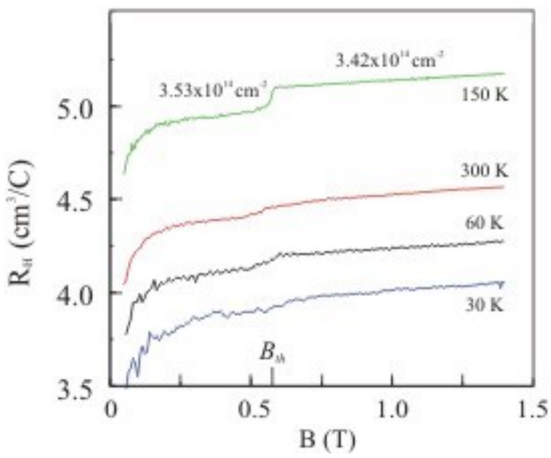

Fig.2 Absolute value of the Hall coefficient as a function of magnetic field at four temperatures showing a step-wise change at the threshold magnetic field of B_{th} = 0.58 T

Magnetic field dependencies of the Hall coefficient R_H at different temperatures are plotted in Fig. 2. Except at very low magnetic fields (where the accuracy is low) the R_H remains nearly constant showing only a positive step−wise change at the threshold magnetic field B_{th} = 0.58 T. The step is observable in the entire temperature interval of measurements and is the most prominent at 150 K, where R_H obtains maximum values and thus the parallel conductance of the cladding layer is minimized. The linear behaviour of the R_H outside the region of the threshold magnetic field gives us an opportunity to treat its inverse values as net free electron concentrations in the entire sample.

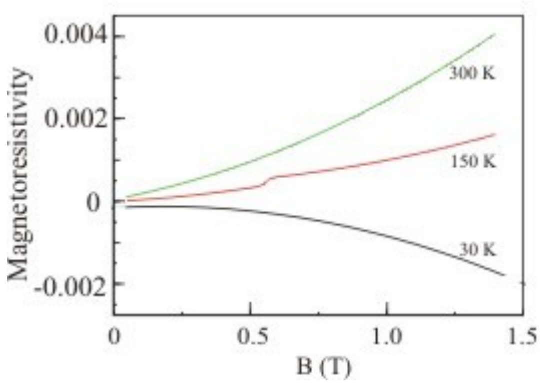

Fig.3 Magnetoresistanse (MR) at three temperatures. A step-wise change at the same threshold magnetic field B_{th} = 0.58 T is visible at 150 K.

Figure 3 shows magnetoresistivity (MR) curves at three selected temperatures. It is seen that the MR is relatively weak and it changes from positive values at 300 K to negative values at 30 K. We point out that a step−wise positive change is revealed in the MR curve at 150 K at the same threshold magnetic field B_{th} . This step occurs in all the MR curves measured down to 60 K (not shown in the figure) and also indicates a magnetic field induced reduction of the carrier concentration. Thus, having in mind the similar step−wise behaviour of the R_H and MR, we attribute the step−change of the net free electron concentration to a magnetic field induced localization (freeze out) of carriers confined in the MQW.

3. Model and Duscussion The known model of magnetic freeze−out of carriers in bulk semiconductors [5] is based on the presumption that the magnetic field expands the original spherical wave function of the hydrogen−like ground impurity state into an egg−shaped or, in a very strong magnetic field, into a cigar−shaped function with the longitudinal axes parallel to *B*. The wave function in the plane perpendicular to *B* is respectively compressed which reduces the localization length and enhances the binding energy of the localized states. As a

result, the number of free carriers should be reduced.
Figures 2 and 3 present the Hall effect and MR voltages averaged over the whole sample thickness. We note that the magnetic localization effect in the MQWs we measure is quite weak, because it is reduced on the contacts by the parallel conductance of the thick cladding layer (template). In order to estimate the real effect in the MQW system we relate the measured decrease of electron concentration to the 2D density of states in the MQW, N_{2D}, and to the sheet electron concentration, n_{sh}, of the sample.
We transfer the idea for compressing of the wave function by the magnetic field in the three−dimensional (3D) case [5] to the 2D potential relief near the bottom of conduction band, where the electrons occupying the ground state of the QWs can be spatially localized [1, 2]. The potential relief is treated in the framework of the same theoretical model as the shallow impurity levels, namely the effective mass approximation and a screened Coulomb potential. Hence, we analyze the MQWs treating every well like a quasi−2D system [6, 7] with a cylindrical potential relief having depth of G > kT. The latter approximation is correct since the thickness of the QWs of 4 nm is comparable with the electron Bohr radius in the InGaN and the wells are separated by 10−nm−thick GaN barriers. In such a case, in the description of the fluctuation states, one can restrict the analysis considering the carrier localization in a 2D ground state band, as it was done in Ref. 7 for the exciton luminescence. This moderates the conditions for the occurrence of fluctuation states, compared to the 3D case. The potential minima due to the composition fluctuations can be much deeper than the hydrogen−like impurity state and in the case of InGaN they can reach G = 35 meV [8]. This gives an excellent opportunity for magnetic freeze−out of electrons in InGaN QWs even at 300 K. It is worth noting that all the phenomena forming local states in QWs will, in fact, contribute to the observed magnetic freeze−out of electrons in the studied InGaN/GaN MQW system. For example, an interface disorder could, in principle, additionally freeze−out electrons, as it was suggested in Ref. 6 for the quantum well interface of GaAs/AlGaAs MQW with island−like structures having a thickness of one monolayer. The same should be valid for the influence of the built−in transverse piezoelectric field, i.e. the piezoelectric field would enhance the localization. Then for simplicity we consider further in the analysis only the effect of composition fluctuations on the potential relief.
To estimate the decrease of the sheet electron concentration with increasing magnetic field strength due to the magnetic freeze−out of electrons, we extend the model in Ref. 5 transforming the basic equation from 3D into the 2D case (see also Ref. 9):

$$n_{\mathrm{sh}} = N_{2D}\exp\left[\left(E_F - h\omega_C\right)\right] / k_B T,\ N_{2D} = m_n / 2\pi h^2,\ \omega_C = \left(e / m_n\right)B \qquad (1)$$

The second term in the exponent represents a decrease of n_{sh} due to the applied magnetic field. The number of electrons occupying energy levels in a QW is limited by the 2D density of states, N_{2D}. Even a very small decrease of the free electron concentration in the QW will affect the longitudinal conductance via Eq. (1), which makes the magnetic freeze−out effect stronger in QW systems (and thus measurable) compared to the effect in bulk semiconductors.
In order to quantitatively prove the model we estimate the maximum 2D concentration of the electrons confined in the studied MQW system, $n_{2D}^{\ max} = N_{2D}$. The calculations performed using an effective mass value $m_n = 0.2m_o$, slightly reduced compared with the effective mass in the pure GaN, lead to $n_{2D}^{\ max} = 4\mathrm{x}10^{14}$ cm^{-2}. The respective values of R_H in Fig. 2 transformed into sheet electron concentrations n_{sh}, are shown above the curve recorded at 150 K. It is seen that the measured value $n_{sh} = 3.53\mathrm{x}10^{14}$ cm^{-2} is in a very good accordance with the calculated value of $n_{2D}^{\ max}$. Further using Eq. (1), we estimate the sheet concentration of the magnetic frozen−out electrons in the MQW system. We obtain $n_{sh}(calc) = 1.0\mathrm{x}10^{13}$ cm^{-2}. The experimental value obtained from the respective step in the R_H dependencies (Fig. 1) $n_{sh}(exp) = 1.1\mathrm{x}10^{13}$ cm^{-2} is also in a reasonable agreement with the calculated frozen−out sheet electron concentrations.

4. Summary A magnetic field induced localization of electrons in InGaN/GaN MQW at low magnetic fields and temperatures up to 300 K has been observed. The effect is explained by the influence of localized states due to the composition fluctuations in the QWs. We extend the model for a magnetic induced localization of electrons in InGaN/GaN MQW structures, treating every QW like a quasi−2D system with a cylindrical potential relief. The calculated values of the decrease of the sheet electron concentrations based on such an assumption for the 2D density of states in a MQW system are in a very good accordance with the experimentally obtained values.

References

[1] S. F. Chichibu, T. Sota, K. Wada, S. Nakamura, J. Vac. Sci. Technol. B ***16***, 2204 (1998).
[2] T. T. Deguchi, A. Shikanai, K. Tori, T. Sota, S. Chichibu, S. Nakamura, Appl. Phys. Lett. ***72***, 3329 (1998).
[3] T. Paskova, S. Tungasmita, E. Valcheva, E.B. Svedberg, B. Arnaudov, S. Evtimova, P.A. Persson, A. Henry, R. Beccard, M. Heuken, B. Monemar, MRS Internet J. Nitride Semicond. Res. ***5S1***, W.3.14 (2001).
[4] C. Mavroidis, J. J. Harris, R. B. Jackman, I. Harison, B. J. Ansell, Z. Bourgioua, I. Moeman, J. Appl. Phys. ***91*** (2002) 9835.
[5] Y. Yafet, R.W. Keyes, E.N. Adams, J. Phys. Chem. Solids ***1***, 137 (1956).
[6] T. Takagahara, Phys. Rev. B ***32***, 7003 (1985).
[7] A. Klochikhin, A. Reznitskii, L. Tenishev, S. Permogorov, S. Ivanov, S. Sorokin, K. Mumanis, R. Seisyan, C. Klingshirn, JETP Lett. ***71***, 242 (2000).
[8] S. F. Chichibu, T. Azuhata, T. Sota, T. Mukai, Appl. Phys. Lett. ***79***, 341 (2001).
[9] K. Zeeger, *Semiconductor physics*, (Springer, Heidelberg, 1997), p. 305.